THE INFLUENCE OF HYDRIDE DISTRIBUTION ON THE FAILURE OF ZIRCALOY

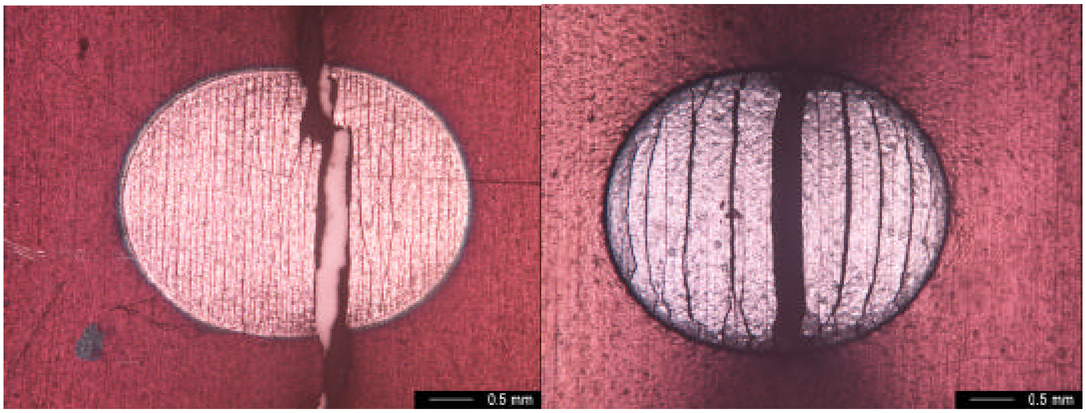
O.N. Pierron[1], R.S. Daum[2], D.A. Koss[1], A.T. Motta[1], and K.S. Chan[3]
[1]Penn State University, University Park, PA 16802
[2]Argonne National Laboratory, Argonne, IL 60439
[3]Southwest Research Institute, San Antonio, TX

After in-reactor exposure, irradiated Zircaloy cladding tubes often contain hydrides that concentrate near the outer surface either in the form of a continuous hydrided layer or as a hydride blister. We have investigated the fracture behavior of unirradiated Zircaloy-4 sheet (0.64 mm thick) containing either solid hydride blisters or a continuous hydrided layer/"rim" at both 25° and 300°C and subject to the multi-axial stress state of near plane-strain tension. This state of stress is a reasonable approximation of the state of stress observed during an RIA in the absence of strong pellet-cladding bonding. The use of sheet material allowed greater freedom in the specimen design so that we could introduce blisters of a realistic size but that would be still compatible with the gauge length used. Importantly, the Kearns factors [1]of the sheet are similar to those of Zircaloy cladding tubes so that the sheet has crystallographic texture similar to that of tubing. The "blisters" were prepared by hydrogen charging both cold-worked stress relieved and recrystallized Zircaloy sheet using a Ni window, the geometry of which controlled the geometry of the blister. Both the blister diameter and the blister thickness were varied.

The results show that the fracture strains obtained with *sheet* material containing a hydride rim are very similar to those obtained previously on *tubing* with hydride rim, which gives confidence that the information on sheet material has relevance for tubing. As shown in Figure 1, the blisters tend to be brittle, and the overall failure of the Zircaloy is controlled by fracture of the remaining "substrate" material. In fact acoustic emission experiments reveal that the blisters crack shortly after yielding. Figure 2 shows the local fracture strain plotted against blister depth, for both room temperature and 300°C experiments. These experiments indicate that fracture of the sheet is sensitive to the depth of the hydride layer/blister such that there is a significant decrease in ductility as the blister depth increases, up to a depth of about 100 micron. Beyond this value the ductility remains approximately constant. Importantly, moderate ductility is retained in the Zircaloy at 300°C even for blisters of depths > 200 microns, even though such blister depths severely limit room temperature ductility. In general, the ductility of a material with a continuous hydride rim is less than that of a material containing blisters of the same depth. This is likely due to the limited size of the cracks formed in the blister material.

The higher ductility of the sheet material at higher temperature appears to be related to the fact that the fracture strain of the hydride precipitate particles within the substrate increases with increasing temperature. The resulting increase in void nucleation strain contributes to a significant increase of the fracture toughness at high temperatures. As a result, experimental evidence as well as analytical modeling indicates that, while substrate fracture is controlled by crack growth at 25°C, the inhibition of crack growth at 300^0C results in eventual failure due to an onset of a shear instability process. As a result, the Zircaloy remains relatively "tolerant" of hydride blisters at 300°C.

[1] The Kearns factors are the resolved fractions of basal poles aligned with the three macroscopic directions: rolling, transverse and normal for sheet material and axial, tangential and radial for tubing, respectively.



(a) (b)

Figure 1.. Macrographs of cracked blisters in CWSR material failed at (a) 25^{0}C and with a 50 µm deep blister and (b) 300^{0}C with a 105 µm deep blister.

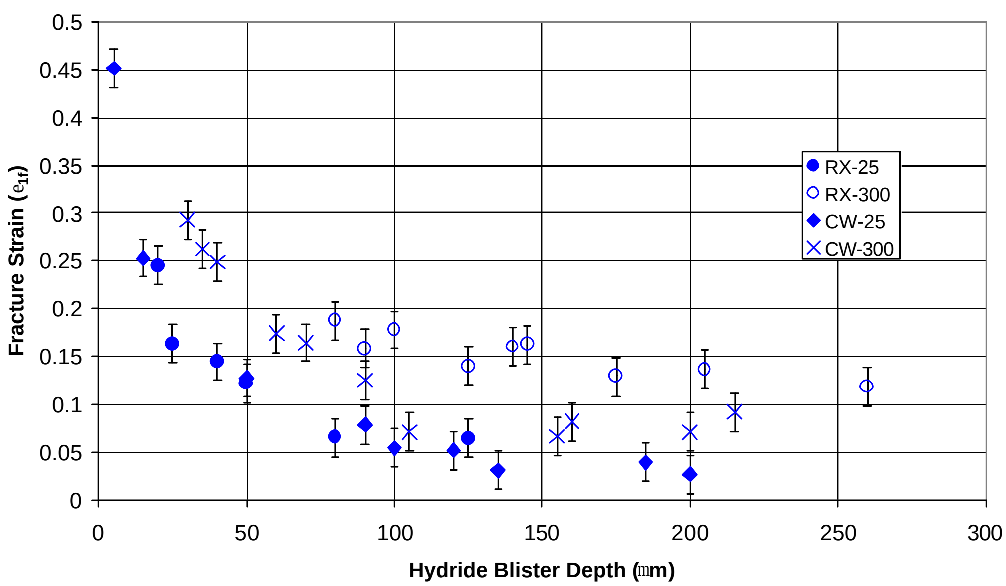


Figure 2. The local fracture strain as a function of hydride blister thickness for both cold worked and stress relieved (CWSR) and recrystallized (RX) Zircaloy-4 sheet tested at either 25^{0}C or 300^{0}C. All data are for 3 mm blisters.